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Comparative Evaluation of Nitrogen Release Patterns from Controlled-release Fertilizers by Nitrogen Leaching Analysis

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Abstract. **Seven nursery grade (8–9 month duration), polymer-coated, controlled-release fertilizers (CRF) were topdressed or incorporated into a 2 peat : 1 vermiculite : 1 sand (by volume) medium to yield the same amount of N per container. The pots (0.5 L) were uniformly irrigated with DI water every week to produce a target leaching fraction of 25%. Leachate N contents (ammonium plus nitrate), employed as indicators of N release, allowed for comparison of CRF performance as a function of temperature changes over a season. Two distinct N leaching (i.e., release) patterns were observed over the 180-day experimental period. The fertilizers Osmocote 18–6–12FS (Fast Start: OSM-FS), Prokote Plus 20–3–10 (PROK), Osmocote 24–4–8HN (High N: OSM-HN) and Polyon 25–4–12 (POLY) exhibited a N leaching pattern that closely followed changes in average daily ambient temperatures (T_{avg}) over the season. This relationship was curvilinear, with N leaching rates per pot (NLR) being highly responsive to T_{avg} changes between 20 and 25 °C. Temperatures above 25 °C produced an average maximum NLR of 1.27 mg·d^{-1} for these fertilizers. OSM-FS, PROK, and OSM-HN had the highest cumulative N losses over the experimental period. In contrast, the CRF group formed by Nutricote 18-6-8 (270: NUTR), Woodace 20–4–12 (WDC), and Osmocote 18–6–12 (OSM) showed a more stable N leaching pattern over a wider range of temperatures, with rates about 30% to 40% lower than those in the temperature-responsive CRF, and averaging a maximum NLR of 0.79 mg·d^{-1} for T_{avg} >25 °C. NUTR and WDC had the lowest cumulative N losses over the season. Soluble salt readings paralleled N leaching for each CRF, indicating similar leaching patterns for other nutrients. Incorporation produced significantly higher cumulative N losses than topdressing, but without effect on the actual N leaching pattern over the season. Regardless of the N formulation in the CRF, over 85% of the N recovered in the leachates was in the nitrate form.**

Fertility programs for container nursery stock are typically based on slow- or controlled-release fertilizers (CRF). In theory, use of these fertilizers offers several advantages over liquid feeding (LF): avoidance of high initial salt levels in the growing media, provision of a gradual, localized long-term nutrient supply that improves fertilizer use efficiency, and reduced nutrient leaching losses (Bunt, 1988; Maynard and Lorenz, 1980). Use of CRF also resulted in equivalent or enhanced plant growth compared to plants fertilized by LF (Johnson et al., 1981; Wright and Niemiera, 1987).

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There are, however, some problems associated with the use of CRF. Perhaps the most prevalent complaint is that nutrient release from CRF does not parallel plant nutrient demand. Relatively high nutrient release may occur at the beginning of the growing season when plants are small and their nutrient requirements lower, and the opposite happening later in the season (Wright and Niemiera, 1987). Meadows and Fuller (1983) reported that nutrient release periods from several CRF, particularly polymer-coated materials, were typically shorter than those claimed by the fertilizer manufacturers. Such differences have been attributed to the determination of nutrient release periods under laboratory conditions that are not representative of those encountered during commercial plant production (Patel and Sharma, 1977). As release from many polymer-coated CRF is temperature dependent (Oertli, 1980; Oertli and Lunt, 1962), CRF longevity ratings by most manufacturers are established at a base temperature, usually 21 °C, which is not representative of the average temperatures found in the growing medium (Davidson et al., 1994; Martin and Ingram, 1988) or even that in the air (ambient) during most of the growing season.

Besides the establishment of actual release periods for CRF, perhaps more attention should be given to individual CRF nutrient release pattern over the season, particularly their stability over the range of temperature conditions encountered during production. Such information would be more helpful, than longevity ratings, in managing nutrient levels during production. The objective of this study was to compare the patterns of N release from selected nursery-grade, polymer-coated CRF in relation to ambient temperature changes during a growing season. To this end, patterns of N leaching losses under managed irrigation conditions were used as indicators of N release.

Materials and Methods

Seven CRF were selected, based on their prevalence in nursery crop production, similarity of nutrient (N–P–K) composition and release period (8–9 months) (Table 1). The fertilizers have all or most of their controlled-release characteristics based on various polymer coatings. In addition, the materials have differences in their N formulations, both in form and proportion of the total N analysis (Table 1).

A growing medium was prepared by mixing 2 sphagnum peat : 1 vermiculite : 1 sand (by volume). The medium was amended with dolomitic limestone and Micromax trace element mix (Scotts, Marysville, Ohio) at 2.4 and 0.6 kg·m^{-3}, respectively; 0.5-L plastic pots were filled with the medium. The bottom of the containers were lined with a fabric barrier to avoid medium losses through the drainage holes. The seven CRF were applied at rates that yielded 0.38 g N per container. This rate corresponds to the intermediate label rate recommended for OSM (5.35 kg·m^{-3}), which was used as the standard reference for this study. CRF were evenly distributed (topdressed) over the medium surface. Two of the fertilizers (OSM and POLY) also were incorporated into the medium to evaluate the effect of application method on N leaching characteristics.

The containers were arranged on a greenhouse bench, in a randomized complete-block design with four replications per treatment. All pots were irrigated weekly with sufficient DI water to produce a target leaching fraction of 25%. Water use (evaporation) was determined gravimetrically from selected pots, and used to calculate the volume of water to apply at each irrigation. Leachate from each container was captured in plastic saucer trays. To avoid contamination of the leachate with the medium, the bottom of the container was seated on top of a smaller, inverted container placed in the middle of the saucer tray. Leachate volume was determined 30 min after irrigation and a 20-mL sample was retained for analysis. Leachate electrical conductivity (EC) was determined immediately after collection. The samples were then analyzed for N, or frozen until analysis. Nitrate-N and NH_4-N concentrations in the samples were determined by the diffusion-conductivity method of Carlson (1978, 1986).

The ambient temperature of the greenhouse was monitored hourly by a computer

Table 1. N–P–K analysis and nitrogen formulation of the controlled-release fertilizers used. All fertilizers are rated for an 8–9 month nutrient release period.

Abbreviation	Fertilizer[z]	N–P–K analysis	Nitrogen source[y]
NUTR	Nutricote (270) 18–6–8	18–2.7–6.6	PC NH_4-N (8.6%) and PC NO_3-N (9.4%)
OSM	Osmocote 18–6–12	18–2.7–10	PC NH_4-N (9.7%) and PC NO_3-N (8.3%)
OSM-FS	Osmocote 18–6–12 FS (Fast Start)	18–2.7–10	PC NH_4-N (10.4%) and PC NO_3-N (7.6%)
OSM-HN	Osmocote 24–4–8 HN (High-N)	24–1.8–6.6	PC Urea-N (12%), PC NH_4-N (6.5%), and PC NO_3-N (5.5%)
POLY	Polyon 25–4–12	25–1.8–10	PC Urea-N (21.6%), PC NH_4-N (0.8%), and PC NO_3-N (2.6%)
PROK	Prokote Plus 20–3–10	20–1.3–8.3	PC NH_4-N (7.9%) PC NO_3-N (6.8%), Urea-N (2.1%), and M-Urea (3.2%)
WDC	Woodace 20–4–11	20–1.8–9.1	PC Urea-N (15.2%), IBDU (2.7%), SC NH_4-N (0.8%), and PC NO_3-N (1.4%)

[z]Origin: Osmocote and Prokote from the Scotts Co., Marysville, Ohio; Nutricote from Chisso-Asahi Fert. Co., Tokyo, Japan; Polyon from Pursell Industries, Sylacauga, Ala.; Woodace from Vigoro Industries, Fairview Heights, Ill.
[y]PC = polymer coated; SC = sulfur coated; M-Urea = methylene urea; IBDU = isobutyledene urea.

that recorded maximum, minimum and calculated average daily temperatures. Temperature sensors were placed about 1 m above the containers.

The experiment was conducted from 14 Apr. to 11 Oct. 1995. Cumulative N leaching data from topdressed fertilizers over this period were analyzed by GLM procedures and mean separation by Tukey's HSD (SAS Institute, 1990). Patterns of N leaching for each CRF were plotted over time using leachate N contents reported on a daily basis [(N concentration × leachate volume)/time interval in days]. Regression analyses were performed with N leaching rates as the dependent variable and average daily ambient temperatures as the independent variable. Data from the two fertilizers that were incorporated were analyzed in combination with data obtained when they were topdressed. This procedure allowed a 2 × 2 factorial analysis, with fertilizer type and mode of CRF application as tested factors.

Results

Two distinct patterns of N leaching were observed among the CRF over the 180-d experimental period (Fig. 1). Nitrogen leaching characteristics of two fertilizer groupings became apparent 1 month into the experimental period (mid-May), when the average ambient daily greenhouse temperatures (T_{avg}) exceeded 22 °C and the maximum temperatures (T_{max}) reached 32 °C. OSM-FS, PROK, OSM-HN, and POLY exhibited a N leaching pattern that followed temperature changes over the season (Fig. 1A). This relationship was curvilinear, with N leaching rates (NLR) being highly responsive to temperatures between 20 and 25 °C (Fig. 2A). Over this temperature range, average NLR for these CRF increased 2-fold, from ≈0.5 to 1.2 mg·d^{-1}. Temperatures >25 °C did not result in higher NLR, averaging a maximum of 1.27 mg·d^{-1} for the four CRF (Fig. 2A). At the end of the experimental period, these four CRF had the highest cumulative N losses (Table 2).

In contrast, NUTR, WDC, and OSM showed a more stable pattern of N leaching over the 20 to 30 °C range of temperatures present during the first half of the study (Fig. 1B). The NLR was steady at ≈0.5 mg·d^{-1} over 90 d, until mid-July, when there was a rapid 2-fold increase (Fig. 1B). At this time, the greenhouse T_{avg} reached 30 °C (T_{max} ≈40 °C). Thereafter, N leaching remained high until T_{avg} dropped to <25 °C in mid-September. This leaching profile did not produce a meaningful correlation with T_{avg} (Fig 2B). NUTR, WDC and OSM produced both the lowest NLR for T_{avg} >25°C, and the lowest cumulative N losses over the season (Table 2). Cumulative N losses for these, more temperature-stable, CRF were on average about one-third less than those of the temperature-responsive group (Table 2).

Regardless of the N formulation in the CRF, >85% of the N recovered in the leachate was in the nitrate form (Table 2). The NO_3-N fraction also was high for the incorporated CRF (91% and 95% for OSM and POLY, respectively).

Leachate EC patterns were similar to N leaching, suggesting similar leaching profiles for other nutrients in the fertilizers (Fig. 3). However, and in contrast to NLR, EC values following the first few irrigations were rela-

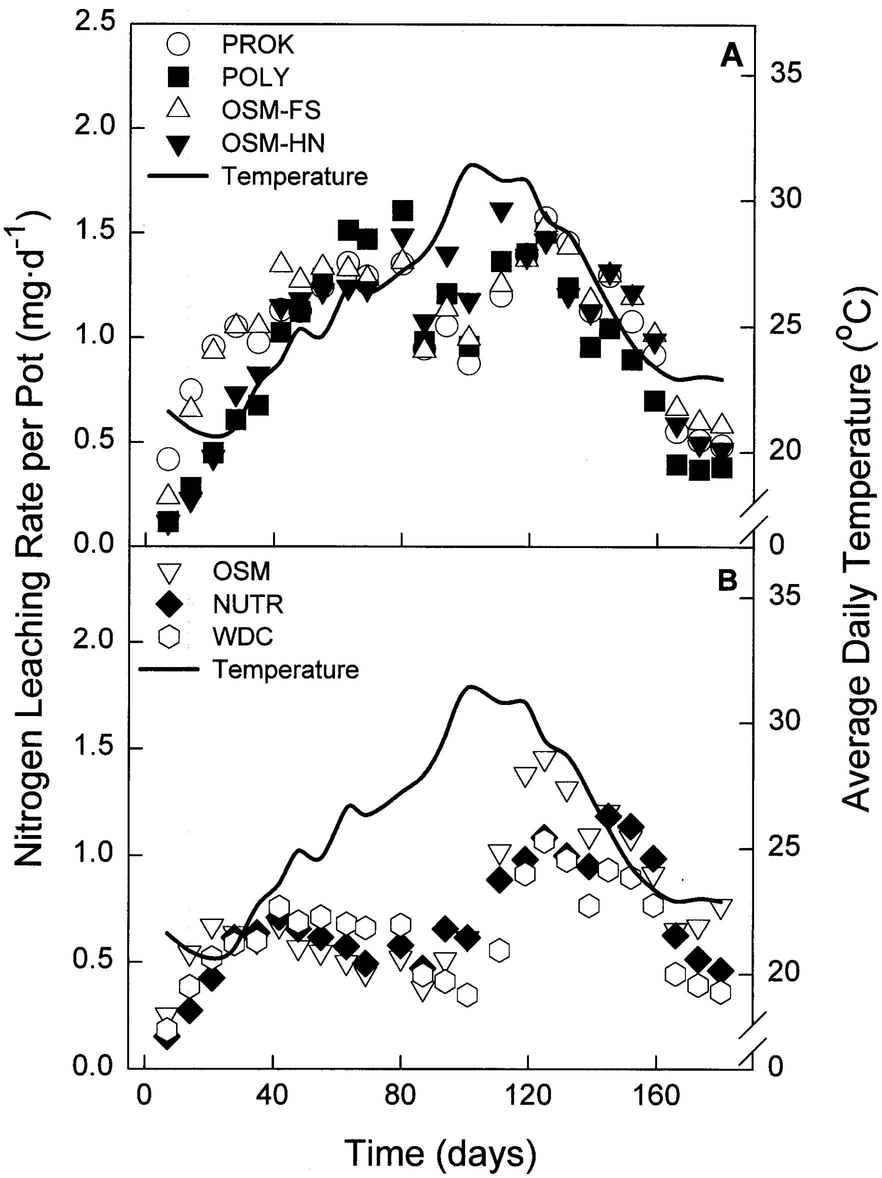

Fig. 1. Nitrogen leaching rates from nursery-grade controlled-release fertilizers topdressed on a 2 peat : 1 vermiculite : 1 sand (by volume) growing medium. Fertilizers were grouped according to temperature responsiveness (A = highly responsive, B = less responsive). Nitrogen data points are the means of four replications and values include NO_3- and NH_4-N. Day 0 = 14 Apr. and day 180 = 11 Oct. 1995.

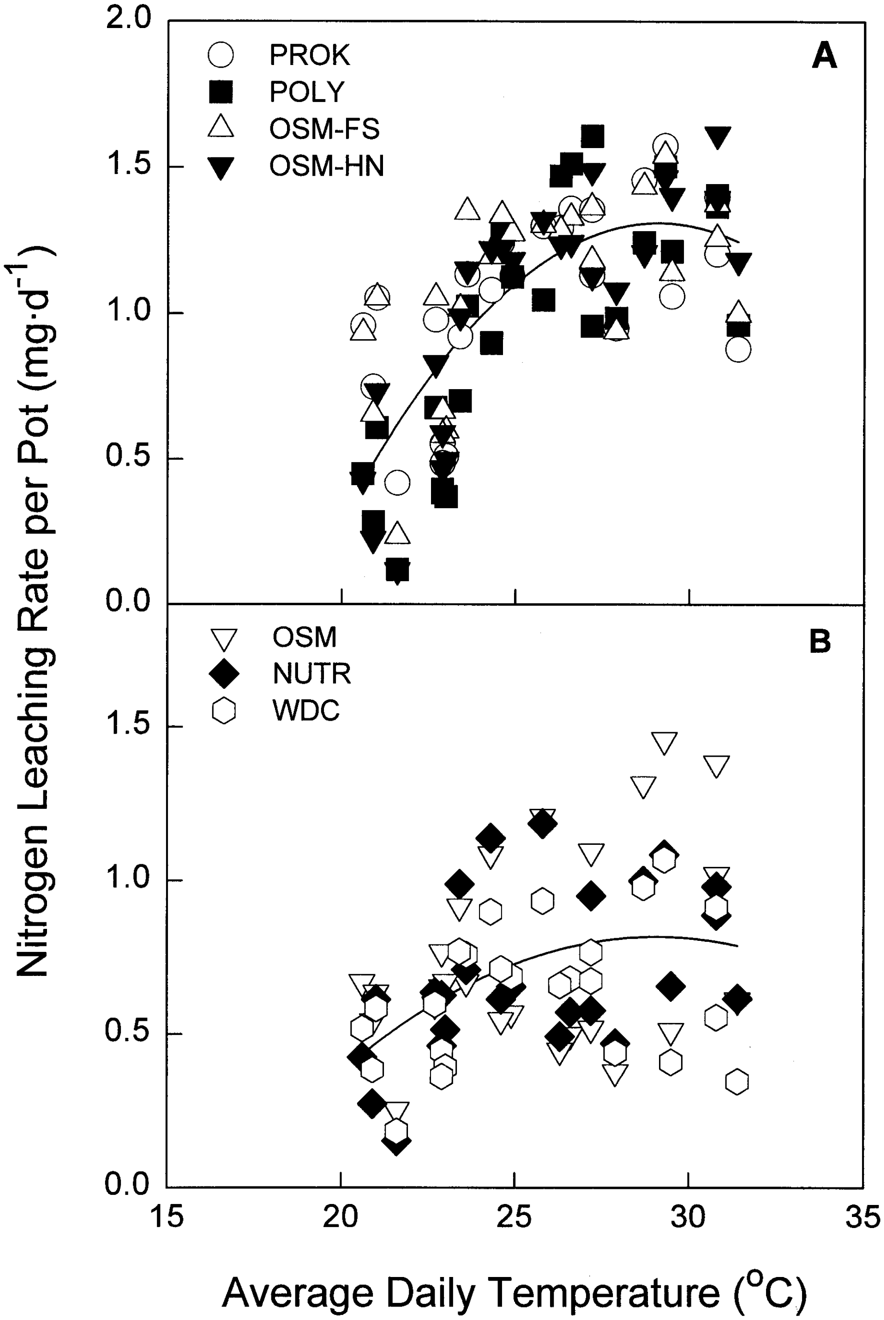

Fig. 2. Nitrogen leaching rates from topdressed controlled-release fertilizers as a function of daily ambient temperatures. Nitrogen data points are the means of four replications and values include NO_3- and NH_4-N. In **A**, the regression equation is $y = -9.021 + 0.710x - 0.012x^2$ ($r^2 = 0.563$), and in **B**, $y = -3.680 + 0.309x - 0.005x^2$ ($r^2 = 0.188$).

Table 2. Average N leaching rates and cumulative N leached from controlled-release fertilizers (8–9 month formulations) topdressed to a 2 peat : 1 vermiculite : 1 sand medium (by volume). Data were collected from 14 Apr. to 11 Oct. 1995 (180 days). All fertilizers were applied to yield 380 mg N per container (0.5 L). Unless specified, N release values include ammonium- and nitrate-N.

	Avg N leaching rate per pot (mg·d^{-1})		Total cumulative N leaching		NO_3-N
Fertilizer	Tavg[z] <25 °C	Tavg >25 °C	(mg/pot)	(% of N applied)	(% of N leached)
NUTR	0.60 a[y]	0.79 c	123 c	32	91 a
OSM	0.66 a	0.87 bc	138 bc	36	86 ab
WDC	0.56 a	0.70 c	112 c	30	88 b
OSM-FS	0.92 a	1.26 a	194 a	51	88 ab
OSM-HN	0.74 a	1.31 a	185 a	49	88 ab
POLY	0.64 a	1.27 ab	168 ab	45	91 ab
PROK	0.86 a	1.25 ab	188 a	50	87 b

[z]Tavg = average daily temperature.
[y]Mean separation (columns) by Tukey's HSD at $P \leq 0.05$.

tively high, but these readings decreased in ≈30 d, and then followed the N leaching pattern.

The method of CRF application had a significant effect on cumulative N leaching, but not on the actual leaching pattern over time (data not shown). Topdressing produced significantly lower cumulative N losses than incorporation (153 vs. 185 mg/pot; $P = 0.005$). However, the fertilizer OSM resulted in significantly lower N losses than POLY (156 vs. 181 mg/pot; $P = 0.016$).

Discussion

Nitrogen leaching from a container is influenced by medium type, irrigation schedule (frequency and volume) and leaching fraction (LF) (Bunt, 1988; Wright and Niemiera, 1987). Under conditions of my study, however, I considered leachate N content a suitable indicator of relative N release patterns for polymer-coated CRF as a function of temperature changes over a season. All pots received the same volume of water at every irrigation to leach a target 25% LF [actual was 27.4 ± 0.3 (±SE; n = 936)], allowing for a direct comparison of N leaching losses between CRF at a point in time. However, the N leaching pattern of a CRF may not be a relative measure of its N release as a function of temperature, but N leaching losses rather may be dictated by temperature effects on irrigation and leachate volumes. This possibility can be excluded, as the average volume of water applied and leached from individual irrigation events was relatively constant over the experimental period [182 ± 5.9 mL (±SE; n = 26) and 49.6 ± 0.6 mL (±SE; n = 936) for volumes applied and leached, respectively]. Regression analysis did not yield a significant relationship between average ambient temperature and leachate volume (best fit was linear, with r^2= 0.01).

Despite the similar longevity rating (8–9 month) of fertilizers used in this study, there were differences in their overall pattern and magnitude of N release. These differences are mainly attributed to polymer coating type, its thickness, or both. The thickness of a polyurethane coating is considered the main factor controlling release from POLY (Goertz, 1993; Pursell Industries, 1994). Similarly, release from Osmocote fertilizers is controlled by the thickness of a copolymer of cyclopentadiene with a glycerol ester (Goertz, 1993; Rutten, 1980; Sharma, 1979). Lower N releases from OSM than from OSM-FS and OSM-HN reflect differences in coating thickness. Another factor that could affect release is the salt composition inside the CRF particle, as salts vary in their ability to absorb water vapor (Bunt, 1988). Salt dissolution rate inside the polymer coating will affect the overall release rate and the relative speeds at which the different elements are released. In the case of the Osmocote formulations used in this study, salt dissolution rate is not likely to contribute significantly to release as compared to the effect of coating thickness. OSM and OSM-FS formulations are mostly based in similar ammonium-nitrate (water solubility ≈1900 g·L^{-1} at

25 °C) contents and yet they had significantly different release rates. In contrast, a lower water solubility of the dominant urea fraction (≈1200 g·L^{-1} at 25 °C) in OSM-HN did not result in lower N release rates than for either OSM or OSM-FS.

Nutricote and WDC had a similar pattern of N release over the season (Fig. 2B), with some of the lowest daily NLR for T_{avg} >25 °C and some of the lowest cumulative N losses over the experimental period (Table 2). Such similarity is attributed to the use of the same polyolefin-polyvinylidene polymer coatings on both CRF (Shibata et al., 1980; Vigoro Industries, 1992). Because these polymers are highly impermeable to water, a release controlling agent like ethylene-vinyl acetate is added to the coating to obtain the desired diffusion characteristics (Goertz, 1993). To minimize the effect that temperature has on the release from this polymer formulation, the manufacturer also adds mineral fillers into the coating (Goertz, 1993). The temperature stability of such formulation was evident in my study, and has also been reported in other comparative CRF studies under laboratory and production conditions. Lamont et al. (1987) compared the release of two 9-month OSM formulations and one 9-month NUTR in water and under a range of temperatures, and found higher release rates for both OSM at all temperatures. A companion container-production study supported these nutrient release differences (Worrall et al., 1987), warning of higher probabilities of plant salt damage with OSM than NUTR under prolonged high temperatures in the growing medium. Plant growth response was, however, generally better with OSM, although plants with high growth rates were not always very responsive to higher nutrient release rates. Conversely, plants believed to respond poorly to fertilizer applications (i.e., low growth rates) responded more favorably to the higher release rates from OSM (Worrall et al., 1987). These findings indicate that specific knowledge of crop nutrient requirements over specific developmental stages and over the growing season is as important as knowing the pattern and intensity of nutrient release from a given CRF.

Despite sharing the same coating technology as NUTR and WDC (Goertz, 1993), PROK had higher N releases, which were closely correlated with temperature over the season (Fig. 2A). Such differences may be attributed to the blending of urea and methylene urea with coated NH_4NO_3 in the PROK formulation. These uncoated urea sources comprise about one fourth of the total N in this fertilizer (Table 1), a fraction likely to produce the observed higher N releases. Although N release from methylene urea is difficult to predict due to its dependency on microbial degradation, any factors affecting microbial activity will have a major influence on release (Barron, 1974; Goertz, 1993; Sharma, 1979). The close relationship between temperature and N release for PROK supports this contention.

Ammonium salts and urea are the most common sources of N found in CRF, primarily due to their low cost compared to nitrate sources (Wright and Niemiera, 1987). When coupled to highly temperature-responsive controlled release polymers, however, dominant ammonium-producing formulations may not be so desirable, as this combination could produce injurious effects on plants sensitive to ammonium (Barron, 1974). OSM-HN (12% urea and 6.5% ammonium) and POLY (21.6% urea) would fall in this category. In an apparent contradiction, >85% of the N captured in the leachates from all fertilizers in the present study was NO_3-N, including those with dominant ammonium-producing sources (Table 2). These observations indicate that nitrification was high in the containers. Furthermore, long residence times of NH_4-N, due to the weekly irrigation intervals used, conceivable allowed for near complete conversion to NO_3-N. Niemiera (1985) found that NH_4-N in a bark medium underwent a complete conversion to nitrate over 2 d. Despite the presence of nitrification in growing media, the temperature-responsiveness (i.e., thickness) of polymer coatings and nitrogen salt formulation need careful consideration from growers, and perhaps revision by manufacturers, if the potential of ammonium toxicity from such fertilizers is to be reduced.

Soluble salt readings recorded throughout the experimental period (Fig. 3) followed the same pattern of release as N (Fig. 2) for all CRF, an indication of similar releases for other nutrients. The relatively high leachate EC at the beginning of the study were likely a result of high salt concentrations in the medium components (Bunt, 1988), immediate nutrient release from CRF particles due to broken or imperfect coatings (Lamont et al., 1987), or a combination of both. This observation supports the recommendation of leaching before or at transplant and exercising careful handling and storage of CRF (Bunt, 1988).

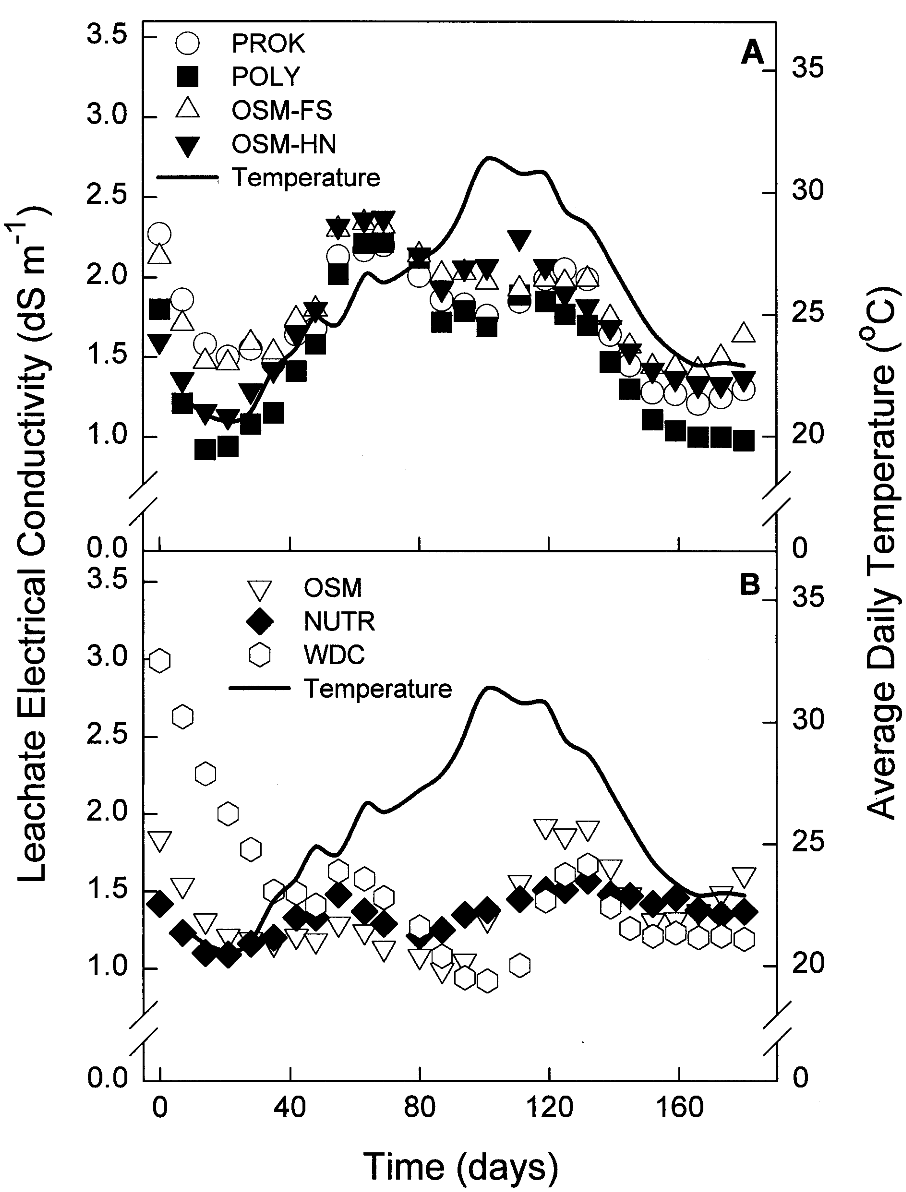

Fig. 3. Electrical conductivity in leachates collected from nursery-grade controlled-release fertilizers topdressed on a 2 peat : 1 vermiculite : 1 sand (by volume) growing medium. Fertilizers were grouped as in Fig. 1. Data points are the means of four replications. Day 0 = 14 Apr. and day 180 = 11 Oct. 1995.

The method of CRF application had a significant effect on cumulative N losses, but not on the release pattern. Topdressing resulted in lower N leaching than incorporation. The time for transfer of nutrients through membranes in topdressed coated-fertilizers is presumably extended over incorporation due to intermittent drying of the upper growing medium layers between irrigations (Barron, 1974; Lunt and Oertli, 1962). Drying of the medium will slow the diffusion of water vapor into the fertilizer, the rate limiting step for nutrient release in membrane coated CRF (Kochba et al., 1990). I irrigated pots only once a week, allowing for such a possibility. Relatively high temperatures and heat loads that are typically found in container media (Martin and Ingram, 1988) could also be contributing to higher nutrient releases for incorporated CRF as compared to topdressing. Besides the actual N release characteristics of the CRF, the physical placement of the fertilizer could contribute to lower nutrient leaching losses from topdressed containers than those with incorporated CRF. As nutrients are released from topdressed CRF and travel throughout the growing medium profile, the chances of being adsorbed by the medium and absorbed by the plant are increased. In contrast, if the CRF is distributed throughout the medium, nutrients released from CRF particles located in the lower portion of the pot will be less available for medium retention and plant uptake, thus leaching more readily and contributing to higher total nutrient losses.

In summary, results from this study indicate that despite similar longevity ratings, the intensity and pattern of nutrient release can be significantly different among polymer-coated CRF. Knowledge of the release behavior from CRF and their response to environmental variables like temperature would allow managers to tailor fertilizers to specific crop nutrient demands, the ultimate objective in the development of highly efficient fertilization programs for container crops (Wright and Niemiera, 1987).

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